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An investigation of an upper level vortex.

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AN INVESTIGATION OF AN UPPER LEVEL VORTEX

BY

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PREFACE

The purpose of this investigation is to give a detailed study to a large scale cold core cyclonic disturbance at upper levels. The investigation was instigated by discussion with Airline and Weather Bureau people who must contend with the problem of forecasting upper level winds.

It is felt that advance information on the development of an upper level vortex would be very valuable as an aid in the forecasting of upper level winds for flight operations.

This investigation is limited to the analysis of one such disturbance which occurred over the Western United States during October 1949.

The discussion is centered about the 500 millibar level which is considered the approximate flight level of the present day military and commercial aircraft.

The author wishes to express gratitude for the assistance of G. J. Haltiner, Associate Professor, Department of Aerology, Naval Postgraduate School, Monterey, California.

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I. INTRODUCTION

It is frequently observed that long wave-like disturbances of the middle latitude belt of the westerlies in the upper troposphere increase in amplitude and finally troughs or ridges are cut-off as vorticies from the main current. Such upper level disturbances are observed frequently in such areas as the Azores, Western United States and Eastern Pacific, Midway Island area, and the Western Pacific to name a few. On the other hand an increase in amplitude does not always result in the occurrence of a closed circulation. It appears desirable therefore that further investigation should be made to obtain more knowledge of this phenomenon.

Pressure variation at any level, and specifically in the vicinity of such cyclones, is accompanied by changes in the mass distribution over the disturbance. There are various contributions of advection, divergence, and vertical motions which are reflected in the deepening or filling of the system at the level in question.

In order to arrive at any sound conclusions concerning the forecasting, origin, life history, and dissipation of upper level vorticies it is therefore necessary to study the three dimensional structure of this type of cyclone.

Several papers dealing with this phenomenon have appeared in Meteorological publications and comparisons are made between this system and the lows investigated by others. It can be expected that some differences will occur between this and other such systems because of the limitation that a single vortex is investigated here.

II. PROCEDURE

In order to have a fairly complete three dimensional analysis of an upper level disturbance it was considered desirable to have a complete series of the upper air weather maps for the period from at least forty-eight (48) hours prior to the development of the cyclone aloft through the period of its existence. Due to limitations of time available the author has confined the investigation to the qualitative aspects of the problem. Primarily because ordinary forecasting requires less detail and to improve the continuity and increase the reliability of the results, it was necessary to re-analyze all maps of the period for which the vortex occurred.

Only one main difficulty presented itself in the analysis other than the normal transmission errors. The terrain over which this disturbance occurred was generally above the 1000 millibar level and in some instances above the 850 millibar level. For this reason the investigation was confined to the layer from the 850 millibar level to the 200 millibar level. This eliminated the erros arising from reductions to sea level.

All data for the analyses of the maps was taken from the Daily Upper Air Bulletins for the period 16-21 October 1949. Although uncorrected and by no means complete, they were adequate to accomplish the necessary analyses. Heights, temperature, and dew point at the pressure level were recorded for the Aleutian Chain, the Territory of Alaska, the United States, and one weather ship report in the vicinity of the Gulf of Alaska.

From all the available information analyses were made of the 850 millibar, 700 millibar, 500 millibar, 300 millibar, and 200 millibar levels.

From the consecutive 500 millibar analyses time differentials were made to show the height tendency field over Alaska and the west coast of the United States. A space differential analysis was made for the 850 millibar to 700 millibar layer, the 700 millibar to 500 millibar layer, the 500 millibar to 300 millibar layer, and the 300 millibar to 200 millibar layer. These analyses are discussed later in chapters concerning the advection aspects and height tendency centers.

III. THE SYNOPTIC SITUATION

Important to a discussion of this type is a clear picture of the general synoptic situation associated with the occurrence of the upper vortex under investigation. On 16 October 1949, a cold trough occupied the western section of the United States at the 500 millibar, 300 millibar, and 200 millibar levels (Figure 1) extending from northern Canada to Southern California. The 850 millibar analysis showed a closed low with an extremely flat pressure gradient; while the 700 millibar analysis presented a trough somewhat less pronounced than observed above this level (Figure 2). Over the eastern Pacific Ocean to the west of the trough was the Pacific Dynamic High and to the north over Alaska a cold high was forming and moving southeastward.

On 17 October 1949, the first closed contour appeared at the 500 millibar and 700 millibar levels (Figure 3). The levels above 500 millibars continued to show the trough, much larger in amplitude, however. The slope of the vertical axis between 850 millibars and 700 millibars was large, in the order of 1 to 300. The cold high on the surface from Alaska continued to move southeastward and was intensifying. Pressure was increasing over the northwestern United States and the temperature at all levels over this area was rising.

By 18 October 1949 closed contours appeared at all levels from 700 millibars to 200 millibars. However, the slope of the vertical axis between the 700 millibar and 500 millibar levels was abnormally large (Figure 4).

Further examination of the 700 millibar level analysis indicated the possibility of two centers at that level. One center was displaced some 450 to 500 miles to the east of the low at 500 millibars. Another center

with an odd contour value (9700 at 700 millibars) could be drawn in a position which could be reasonably assumed to be part of the main system at the levels above 700 millibars. Thus, while one cyclone between 700 millibars and 200 millibars was moving south southeast, a weaker, shallow cyclone was moving eastward confined to levels below 700 millibars. There was very little activity associated with the lower level disturbance other than some very light precipitation. The number of closed contours had increased at and above the 500 millibar level. The cold high which had originated over Alaska changed its course from southeast to more easterly. The rate of increase of pressure over the Pacific Northwest had decreased somewhat at this time.

During 19 October 1949 the upper level cyclone reached the southernmost part of its trajectory, and was moving very much slower than previously. The 700 millibar level showed the first even valued closed contour (9800 at 700 millibars) associated with the cyclone above that level. The number of closed contours above the 700 millibar level at all levels continued to increase with the steady increase of pressure in the northern section of the trough. The cold high was moving more rapidly and approaching the lower Hudson Bay region.

By 20 October 1949, a closed contour appeared on the 850 millibar chart below the upper level vortex. The cyclone was now closed at all levels investigated, from 850 millibars to 200 millibars; and it was now moving at a greater speed than on its previous southeastward trajectory.

On 21 October 1949 the cyclone had left the area of high terrain and was proceeding in a northeasterly direction. A closed low appeared only at the levels from 500 millibars on up. The 700 and 850 millibar analyses

showed that only a sharp trough existed in the lower levels. This is possibly due to the change in the altitude of the terrain. The tendency for the formation of a dynamic trough on the lee side of the Rocky Mountains may have masked the low at 700 and 850 millibars. However, this effect was temporary and the closed low developed into the lower levels within the next twenty-four hours. As the system moved eastward a surface low appeared on 22 October with definite frontal structure. The investigation is limited, however, to the period up to 21 October 1949 only.

As observed earlier, the slope of the vertical axis of the cyclone, during its southerly trajectory, was opposite the direction of movement and toward the northwest. The slope became more nearly vertical as it reached the southernmost part of the trajectory and remained so for the rest of the period investigated.

This synoptic study indicates that a complete explanation of the phenomenon of this upper level vortex should include:

1. The origin of the trough.
2. Thermodynamic aspects of a cold core low.
3. The "cut-off" process and the vortex.
4. The vortex movement.

Therefore, the remainder of this study will consider each of the above topics as they pertain to this particular upper level phenomenon.

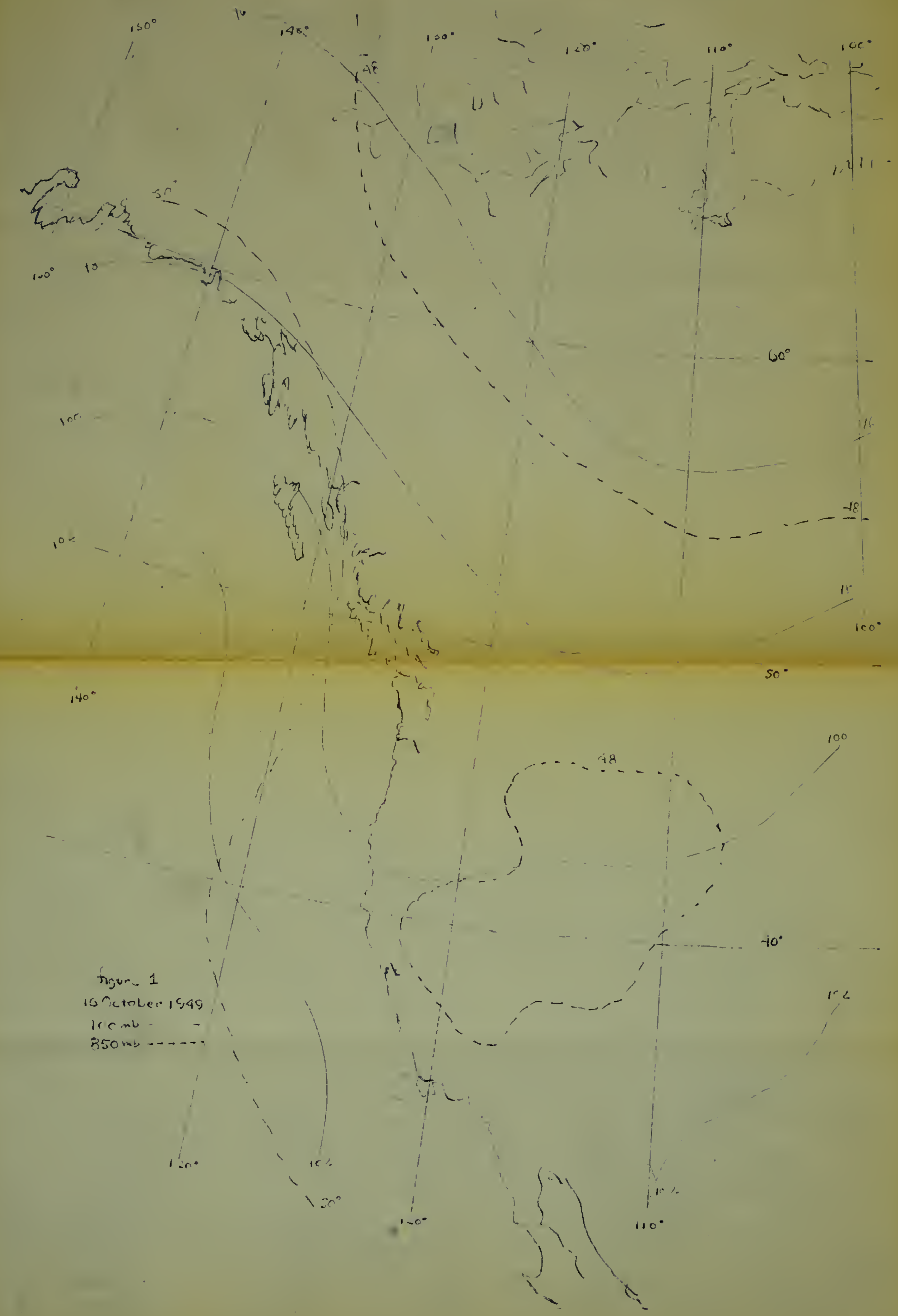


Figure 1
16 October 1949
100 mb ———
850 mb - - - - - -

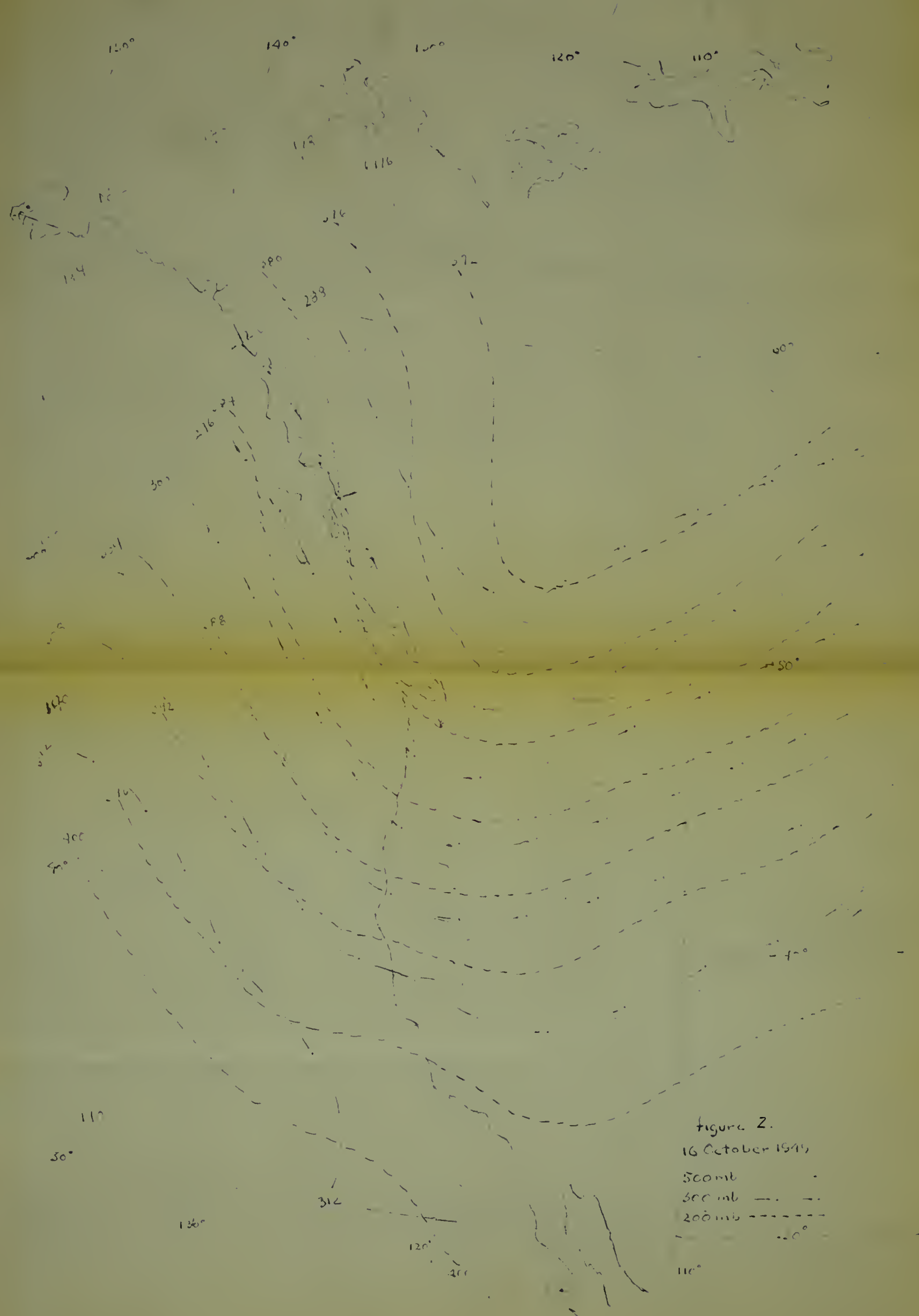


figure 2.
16 October 1949

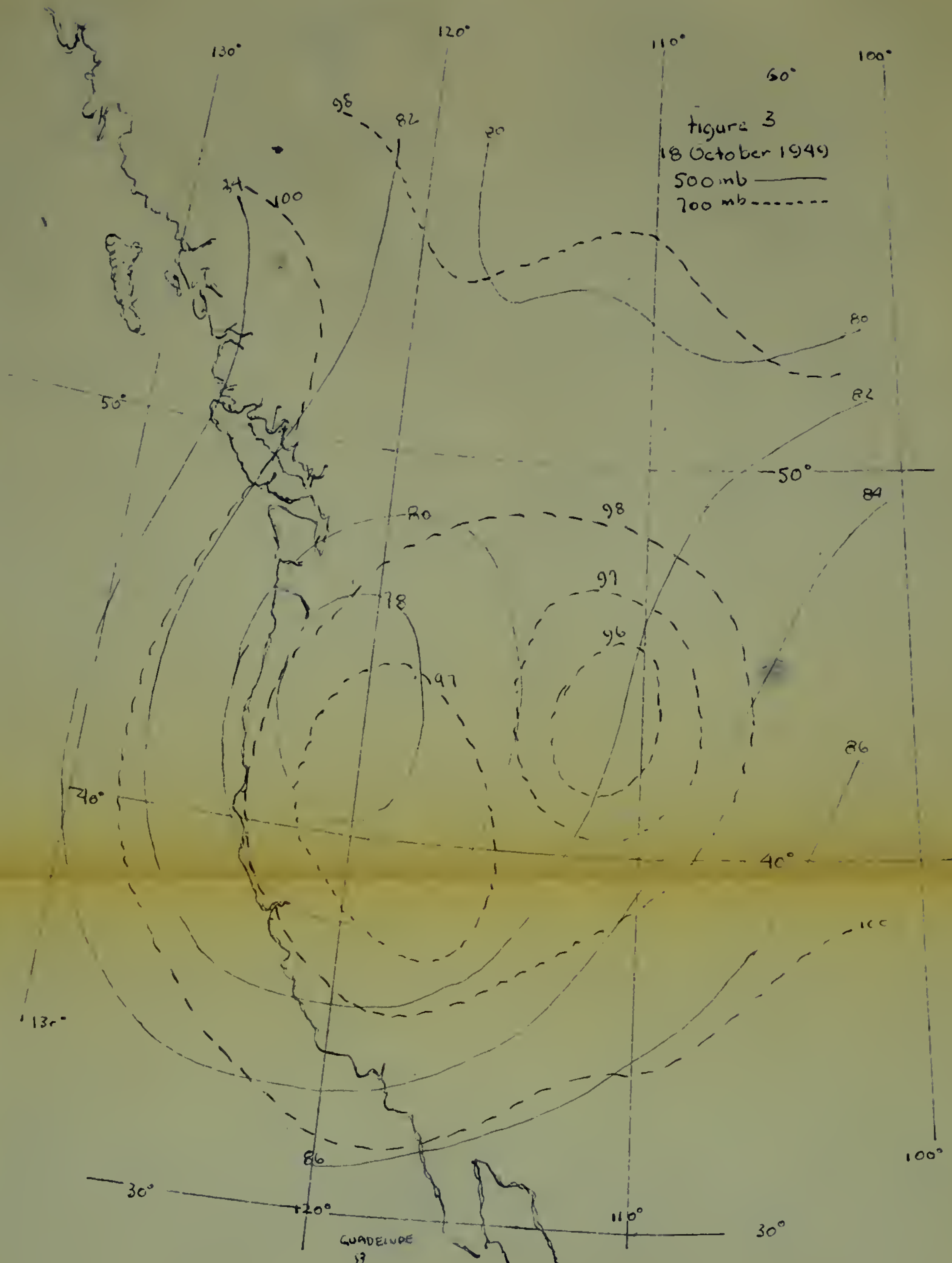
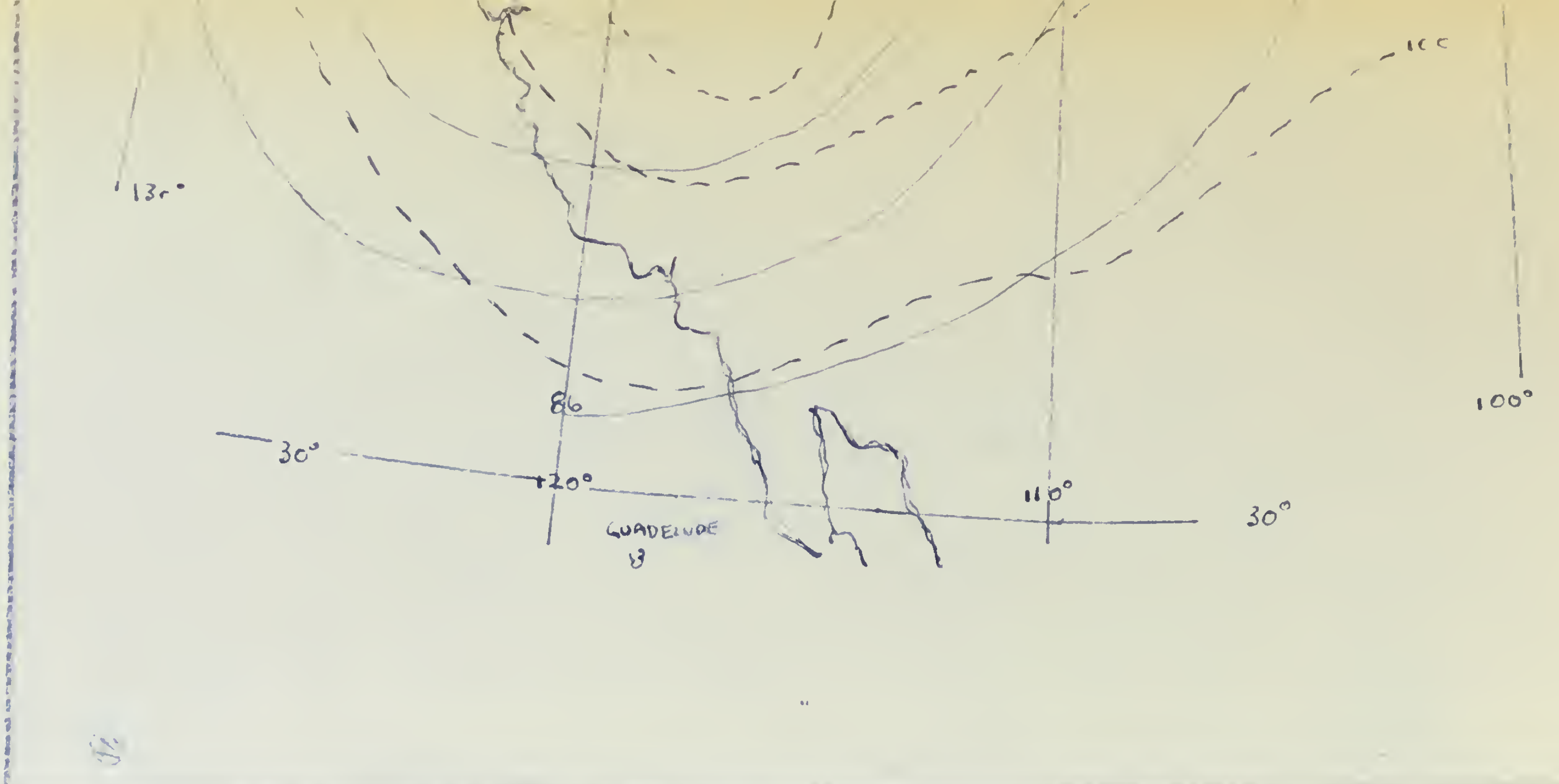


Figure 3
18 October 1949


130°
100°
86
30°
120°
110°
30°
GUADELUPE

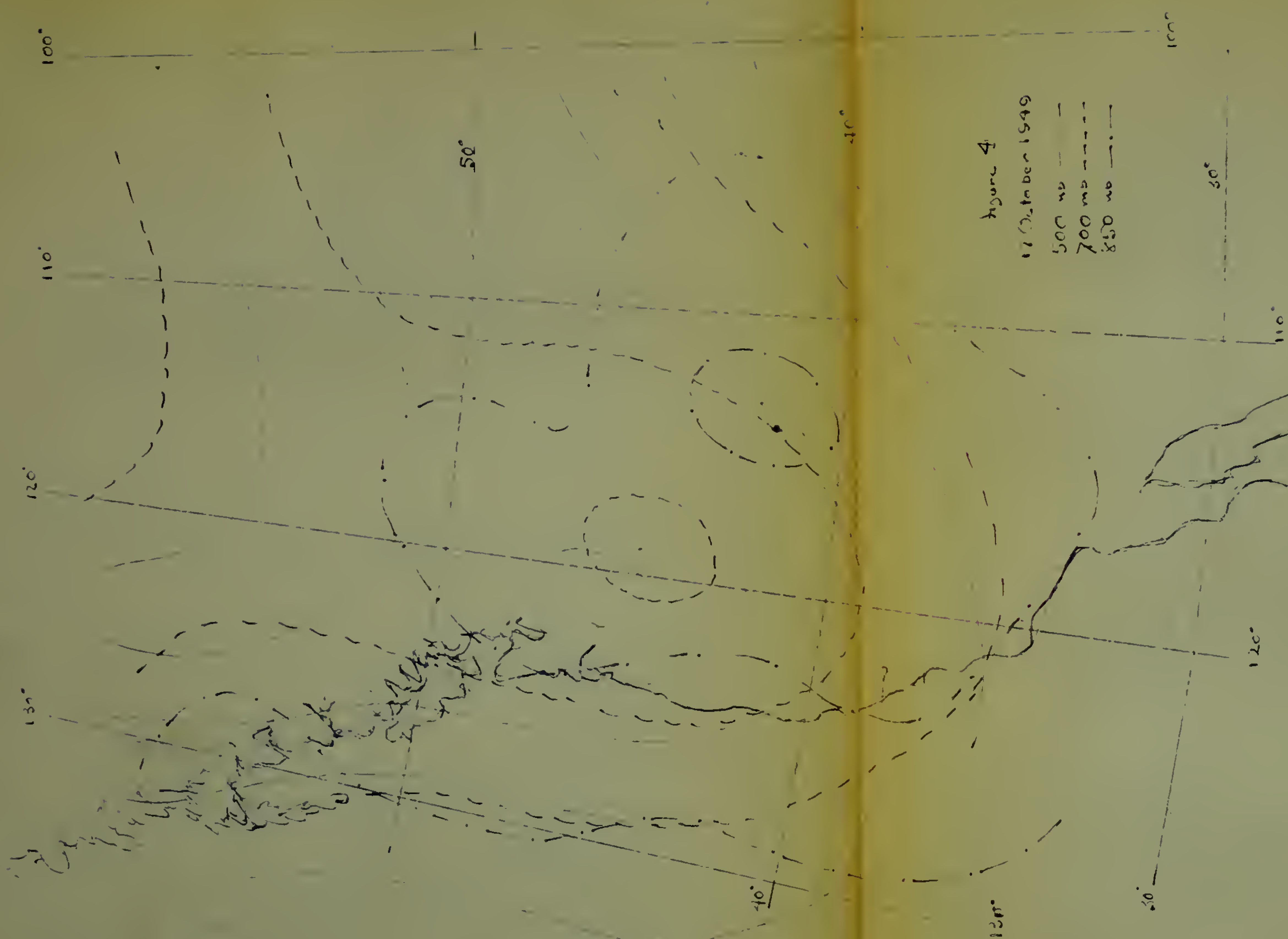


Figure 4
17 October 1949
500 mb
700 mb
850 mb
100°
110°
120°
130°
50°
40°
30°


Figure 4
11 October 1949
500 mb
700 mb
850 mb
130°
120°
110°
100°
30°
30°

IV. TROUGH ORIGIN

Up to the present time there is still no generally accepted theory dealing with the intermittent outbreaks of cold air from the north. Most authors confine themselves to the analysis of the cold core low after the vortex has formed. However, some work is being done concerning such cold outbreaks by considering the dynamics of the stability of the west wind belt. The results according to Hsieh [4] suggest some controlling factors which cause these cold outbreaks; however, theory has not been tested on actual data in the atmosphere.

Since the object of this investigation is to consider all factors which may be or are responsible for the phenomenon which occurred, a possible source of the trough origin will be advanced. In order to accomplish this end it was necessary to trace the synoptic situation for some days prior to the formation of the actual vortex. The following observations were made.

It was noted that on 11 October 1949 the Pacific Polar Front extended from the Gulf of Alaska southwest to the Marianas Islands. On 12 October 1949 a cyclonic disturbance was developing in the Gulf of Alaska at approximately 60° North and 150° West. The frontal wave occluded very rapidly and was developed to upper levels within the following twenty-four to thirty-six hours. This low moved very rapidly eastward. The formation of this disturbance in high latitudes allowed colder air to be brought south by flow from the north in the western section of the low. The trough of this investigation appears to have previously been associated with the low just described. Either the trough aloft stagnated while the system in lower levels moved east and came under the influence of another trough or the trough divided into two troughs, one stagnating and one moving east with the surface system.

Palmen and Nagler 5 have stated that major troughs in the westerlies are the primary regions where pronounced outflow of cold air from the north occurs. Observations show the existence of the cold air into southern latitudes over the western section of the United States.

Figures 5 and 6 consolidate the movement of systems important to the development of the upper level vortex along with the movement of the vortex itself, as discussed in the synoptic situation. All tendency fields refer to the 500 millibar level, which is considered fairly representative of the disturbance as a whole.

As was previously mentioned, a cold high had formed over Alaska and was moving southward as the "cut-off" occurred. This high was reflected by a slight ridge at the 500 millibar level. The positions, time, and intensity of the positive tendency field associated with this cold high are shown in Figure 5. Arrows are drawn to the successive approximate center positions to show the general movement of this tendency field.

The "cut-off" at the 500 millibar level appeared over Oregon on 17 October 1949. The twelve (12) hour positions of the vortex center at 500 millibars are shown in Figure 6 and the track is labeled LOW.

Also included in Figure 6 are the successive 12-hour positions of the center of the negative tendency field associated with the cyclone at 500 millibars.

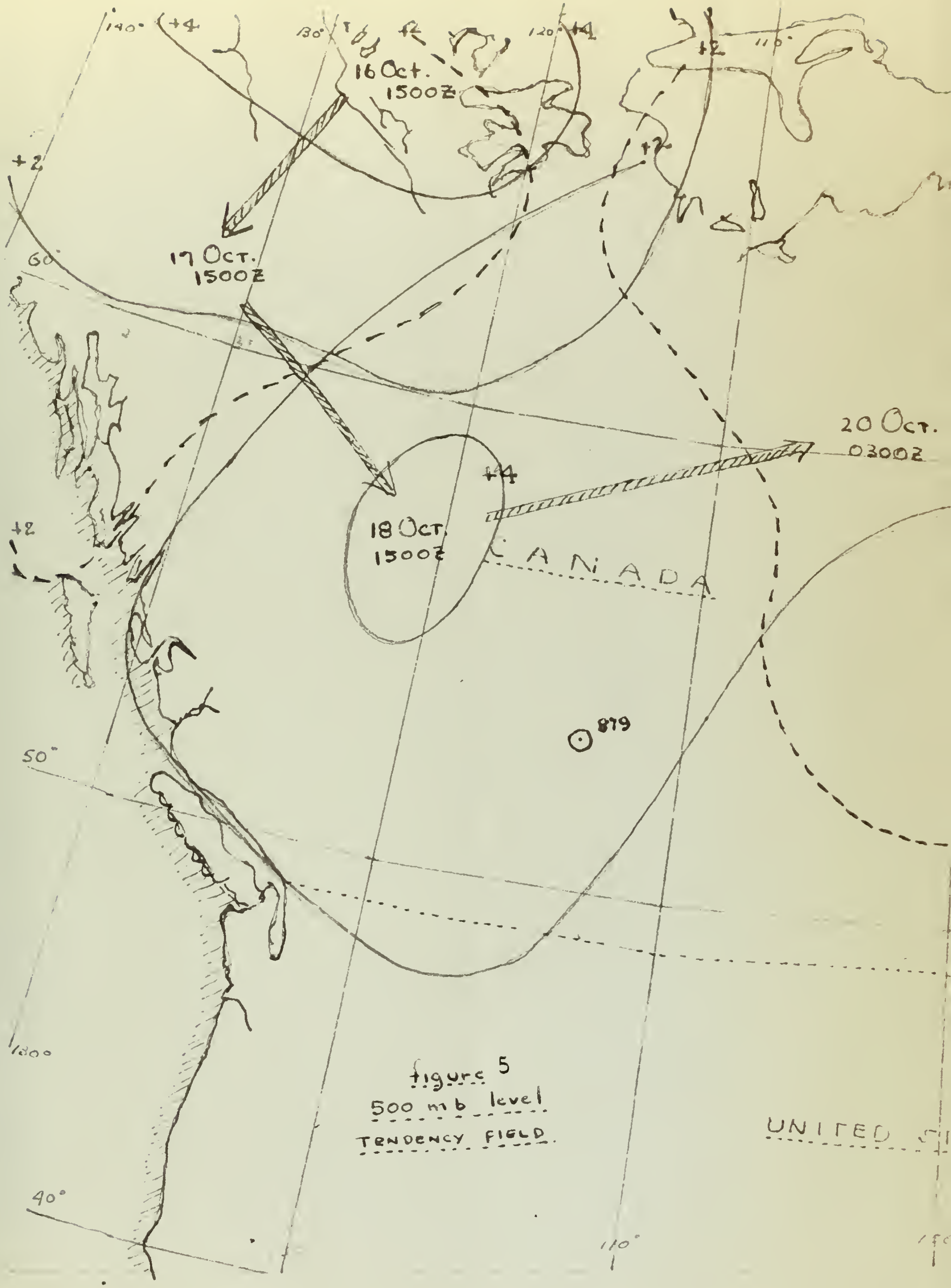
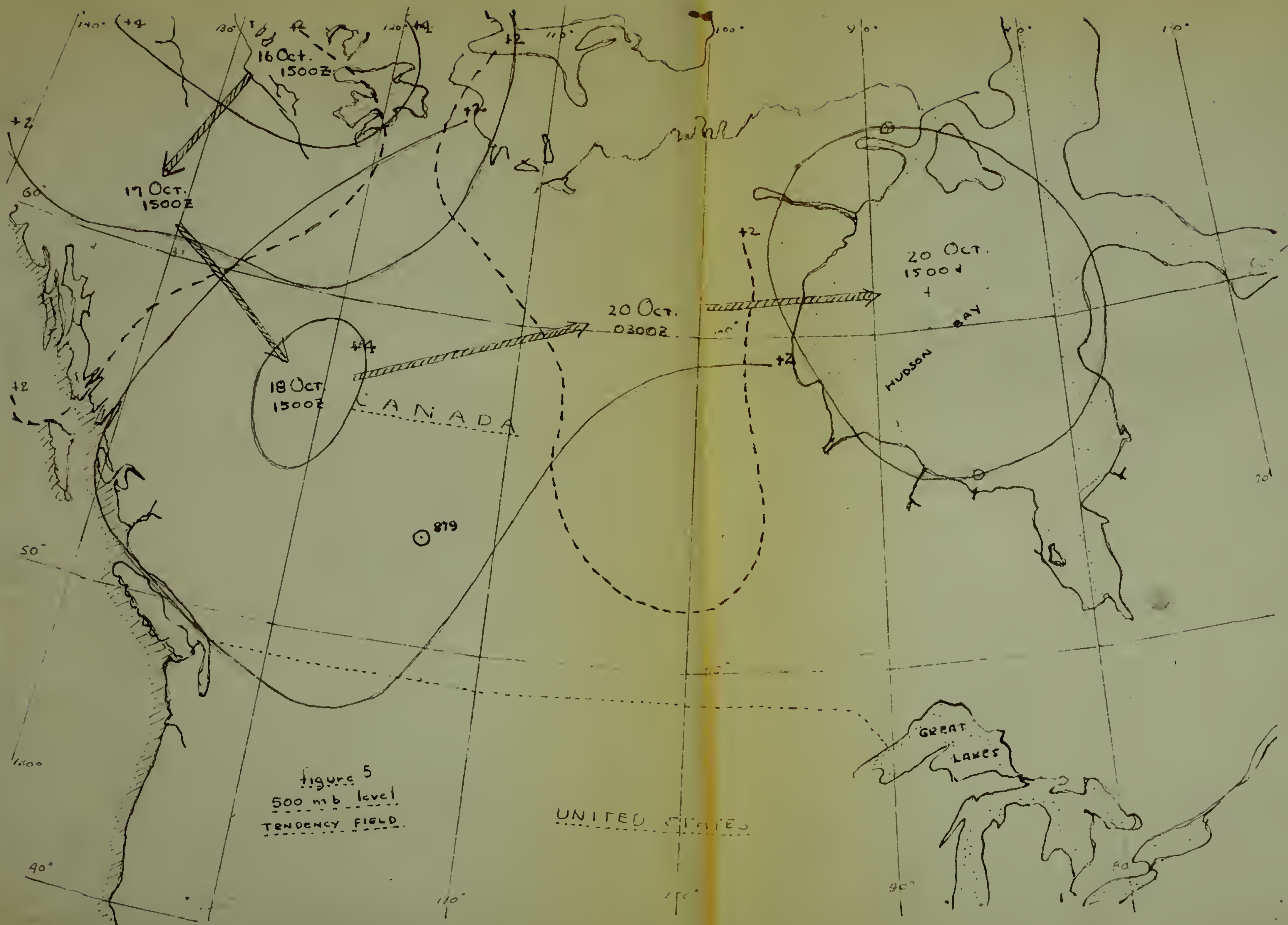
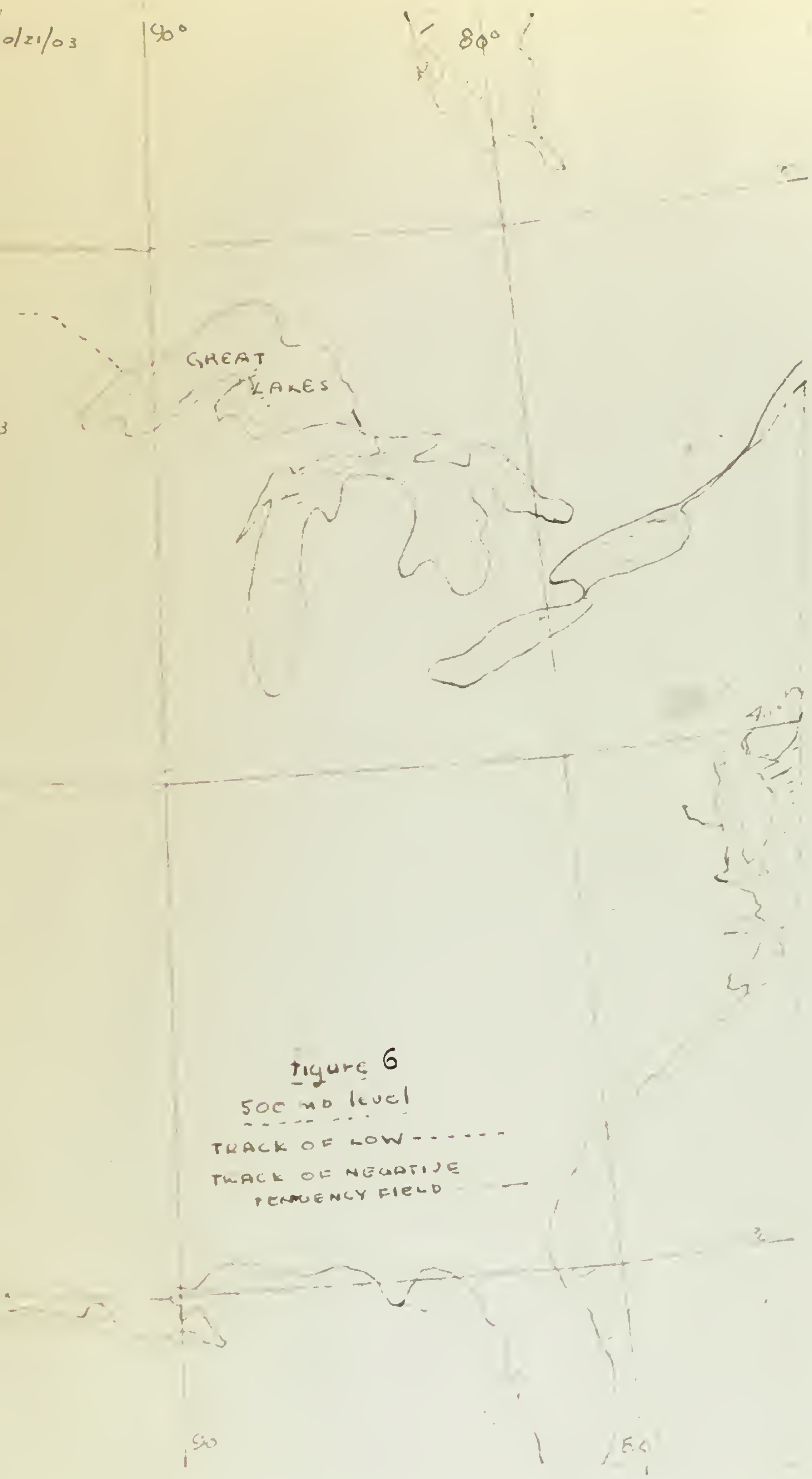


figure 5
500 mb level
TENDENCY FIELD


16 Oct.
1500Z
17 Oct.
1500Z
18 Oct.
1500Z
20 Oct.
0300Z
20 Oct.
1500Z
CANADA
HUDSON BAY
GREAT LAKES
879
figure 5
500 mb level
TENDENCY FIELD
UNITED STATES


100°
90°
80°
70°
+2
20 Oct.
1500 Z
HUDSON
BAY
+2
GREAT
LAKES


120°
110°
100°
90°
80°
CANADA
UNITED STATES
GREAT LAKES
LOW
NEG. TEND. FIELD
10/17/03
10/17/15
10/18/03
10/18/15
10/19/03
10/19/15
10/20/03
10/20/15
10/21/03
figure 6
500 MB level
TRACK OF LOW
TRACK OF NEGATIVE TENDENCY FIELD
KEY
MONTH / DAY / OCT


0/21/03
90°
80°
GREAT LAKES
figure 6
500 mb level
TRACK OF LOW
TRACK OF NEGATIVE TENDENCY FIELD

V. THERMODYNAMIC ASPECTS OF A COLD CORE LOW

The analysis of the isotherm and differential patterns after the vortex has formed, showed that a cold core of air existed in the central portion of the trough. It is easily shown that cold core cyclones increase in intensity with height. The greater changes of pressure with height in the cold core as compared with the surroundings, cause the slope of the isobaric surfaces to become steeper with altitude. Thus, if a cyclone or trough exists at an upper level in a cold column of air, the higher density of the air in the core as compared to its surroundings, will tend to mask the trough or low at the levels below. Figures 1, 2, 3, and 4 show that vortex at the 850 millibar surface is not as well defined as at the 500, 300, or 200 millibar levels.

The rate of change of pressure as given by the hydrostatic equation is,

$$\frac{\partial p}{\partial z} = -g\rho = \frac{gP}{RT} \tag{1.0}$$

The vertical pressure gradient will then be greater for lower temperatures. The mean temperature for layer therefore determines the thickness of the layer. The system under investigation shows the greatest development, at and above the 500 millibar level, becoming more pronounced at lower levels later in the life history.

Figures 7 and 8 show the variations of the heights of the pressure surfaces at the center and to the north of the center, during the period investigated. Noticeable is the small change in height of these surfaces at the center of the vortex, with more pronounced change in the north of the trough, as indicated by the graph of station #879.

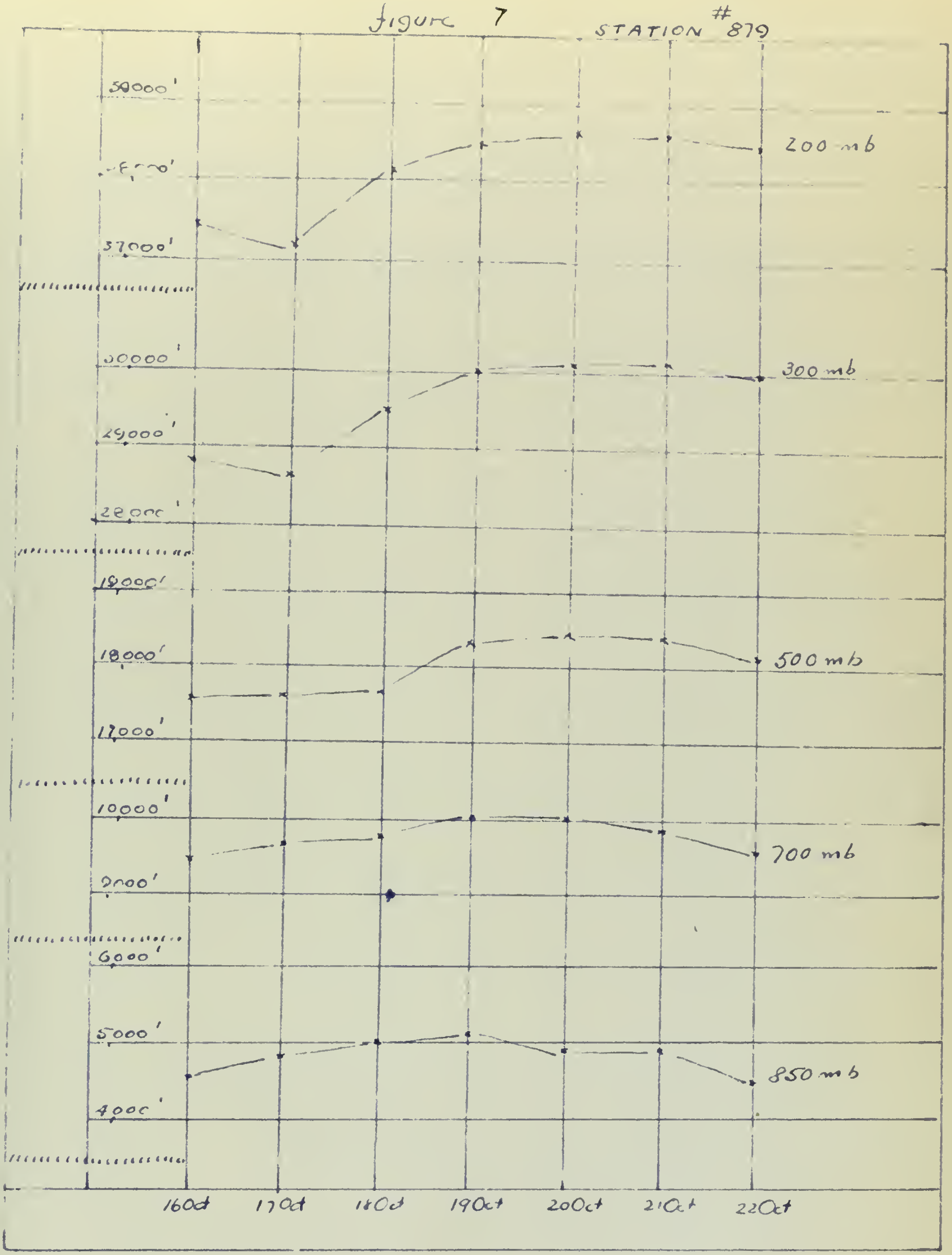


figure 7
STATION #879
200 mb
300 mb
500 mb
700 mb
850 mb
160ct
170ct
190ct
200ct
210ct
220ct

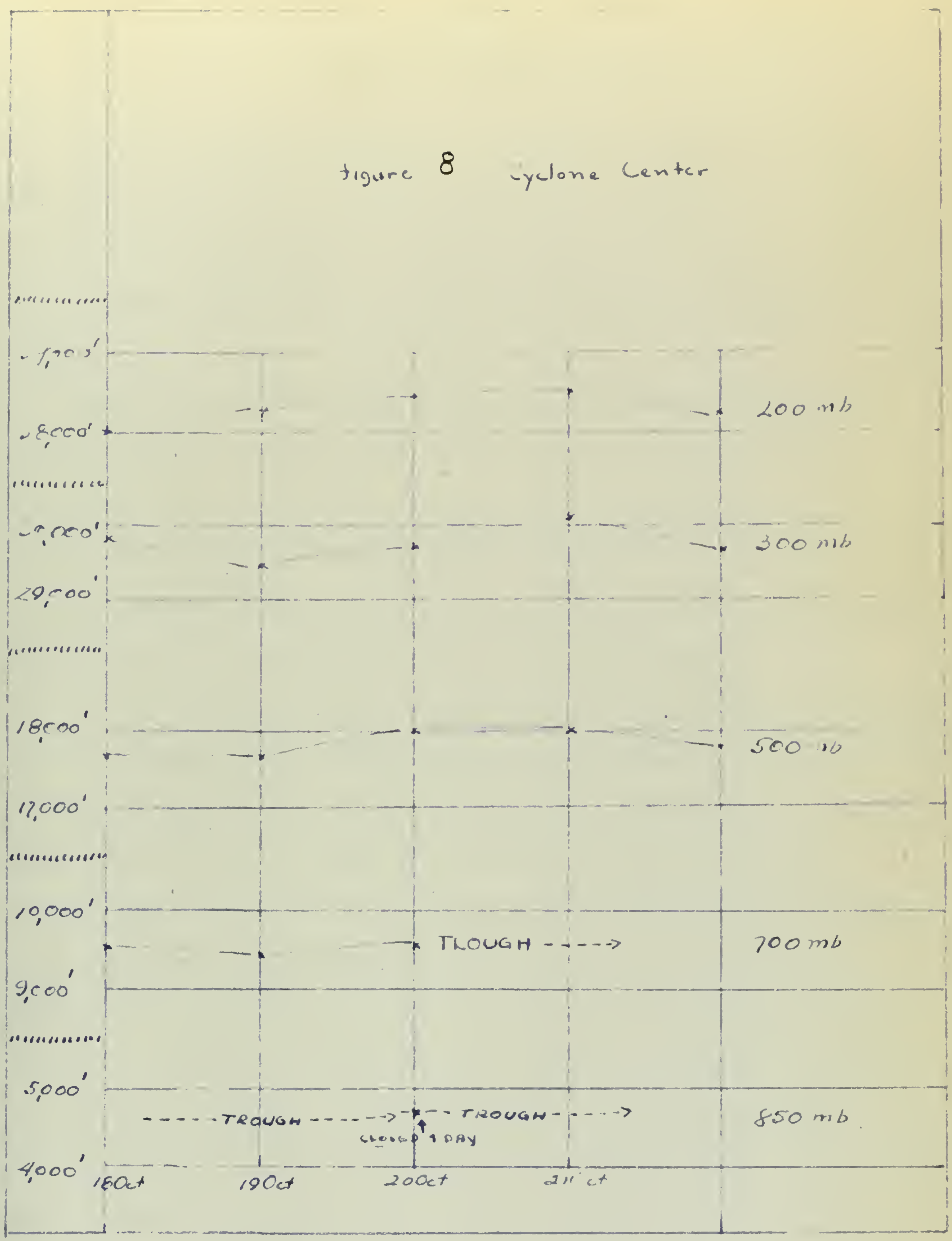


figure 8 Cyclone Center
200 mb
300 mb
500 mb
700 mb
850 mb
TROUGH
TROUGH
TROUGH
CLOSED 1 DAY
18,000'
17,000'
10,000'
9,000'
5,000'
4,000'
16Oct
19Oct
20Oct
21 Oct

VI. THE "CUT-OFF"

From the preceding discussion, it is obvious that there are two requirements that must be fulfilled before the phenomenon of a cut-off vortex in the trough can occur. First is the formation of a cold core in the trough, and second is an increase of pressure in the northern section of the trough.

There are two main processes by which the necessary warming may occur in the north of the trough in order that the cold core may be "cut-off". One is horizontal advection indicated by wind flow normal to the mean isotherms in the differential analyses, and the other is by descending motions in the cold air itself. The warm advection is easily observed, and the descending motions must be investigated.

The 500 millibar analyses are utilized again as being representative of the system as a whole. With the exception of time of occurrence, it is assumed that the processes which accomplish the observed results at 500 millibars are similar to other levels of the system investigated.

Vertical motions were estimated by the so-called "isobaric" technique as described by Panofsky, [6]. The method assumes all motions are adiabatic and that temperature changes are due solely to horizontal advection and vertical motions. The procedure was somewhat simplified by the fact that the contours showed no radical changes from day to day. The results of representative stations, Northwest #798, section I, North #879, section II, Northeast #764, section III, are given in Table 2. The advection expressed qualitatively for the same areas is included in Table 1.

TABLE #1

SECTION I — HORIZONTAL ADVECTION

	DAY / layer	17 Oct.	18 Oct.	19 Oct.	20 Oct.
NORTHWEST	300 TO 200	WEAK WARM	WARM	WEAK WARM	WARM
	500 TO 300	WEAK WARM	WARM	WARM	WEAK WARM
	700 TO 500	WEAK WARM	WARM	WARM	WEAK WARM
	850 TO 700	WEAK WARM	WARM	WARM	NONE
	AVERAGE	WEAK WARM	WARM	WARM	WEAK WARM

SECTION II

NORTH-ALONG CTR LINE	300 TO 200	NONE	WARM	NONE	COLD
	500 TO 300	NONE	WARM	NONE	WEAK COLD
	700 TO 500	NONE	NONE	WEAK COLD	NONE
	850 TO 700	NONE	WEAK COLD	COLD	WEAK WARM
	AVERAGE	NONE	WEAK WARM	WEAK COLD	COLD

SECTION III

NORTHEAST	300 TO 200	COLD	WEAK COLD	WARM	WARM
	500 TO 300	WEAK COLD	WEAK COLD	WEAK WARM	WARM
	700 TO 500	WEAK COLD	WEAK COLD	WEAK WARM	NONE
	850 TO 700	WEAK COLD	WEAK WARM	WARM	WEAK WARM
	AVERAGE	WEAK COLD	WEAK COLD	WARM	WARM

Table 2. clearly indicates that descending motions are present in the northwestern section of the trough. Note also that the height of the 500 millibars surface is rising between 17 and 20 October 1949. Even though the height was increasing, a process which in itself would call for a drop in temperature at 500 mb, the temperature is increasing. This further substantiates the presence of the descending motions. The same situation is occurring in the section to the north along the center line of the trough.

The presence of the general descending motions and pressure increases to the north and northwest implies that there must be considerable horizontal convergence at some higher level. The pressure increase to the north and northwest could be the result of this convergence, thereby establishing an easterly flow and completing the cut-off. Thus a qualitative mechanism has been suggested which causes both the formation of the cold core and the pressure increases in the north of the trough.

Hsieh has advanced the following explanation for the change of wind direction from west to east in the northern section of the trough and the increase of pressure in the north. He observed warm air advection into the northwestern section of the trough, into an area of relatively cold air. The result, termed an "unbalanced solenoidal field", is presented schematically in Figure 9.

Figure 9.

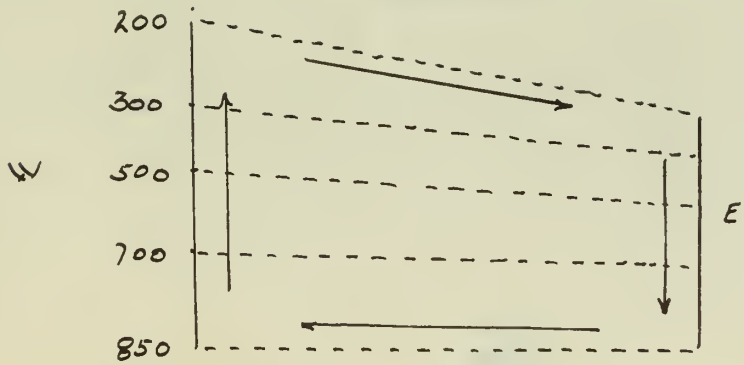


TABLE 2: 500 mb. level

NORTHWEST - SECTION I.

STATION No.	DATE TIME	TOTAL TEMP. CHANGE	CHANGE DUE TO ADVECTION	CHANGE DUE TO DESCENDING MOTIONS	DESCEN MOTION.	HEIGHT OF 500 mb LEVEL
198	17 Oct. 1500Z	-2°C	-4°C	+2°	Yes	17920'
"	18 Oct. 1500Z	+10°C	+1°C	+9°C	Yes	18120'
"	19 Oct. 1500Z	+3°C	+1°C	+2°C	Yes	18600'
"	20 Oct. 1500Z	+4°C	+1°C	+3°C	Yes	18800'

NORTH - SECTION II.

819	17 Oct. 1500Z	0°C	+2°C	-2°C	No	17610'
"	18 Oct. 1500Z	+8°C	+2°C	+6°C	Yes	18020'
"	19 Oct. 1500Z	+8°C	+5°C	+3°C	Yes	18400'

NORTHEAST - SECTION III.

764	17 Oct. 1500Z	-3°C	-3°C	0°C	No	18500'
"	18 Oct. 1500Z	+3°C	+3°C	0°C	No	18560'
"	19 Oct. 1500Z	-1°	-3°C	+2°C	Yes	18610'
"	20 Oct. 1500Z	-1°	-1°C	0°C	No	18430'

Observe the flow in the lower layers is to the west. The result will be a piling up of air to the right (north) of the current which will increase the pressure to the north and at the same time decrease the pressure to the south. This mechanism if applied to the system investigated here would require that: (1) Pressure increase to the north; (2) Ascending motions in the west or northwest; (3) Decrease in pressure to the south. The Hsieh mechanism is not supported in this investigation because: (1) Descending motions are noted to the northwest and north; (2) Pressure shows very little change to the south.

The isotherm analysis of the 500 millibar level showed the first closed isotherm (-35°) occurred on 18 October 1949. On 19 October 1949 the indicated closed cold core had moved to the south with a central closed isotherm of -30°. This general warming in the vicinity of the center continued. The appearance of a closed vortex in the cold column of air precludes the effect of any marked advection within the cyclone. A recent study* of Divergence, assuming gradient wind, of this system for 19 October 1949 discloses that the advection term of the tendency equation up to 300 millibars contributed a negligible amount to the pressure tendency as compared to the other terms of the same equation. Figure 8 shows that the cyclone center has very little change in height at the various pressure levels. It appears evident that there are descending motions in the vicinity of the cyclone center to account for the warming that occurs.

* Unpublished thesis by H. H. Taylor, Lieutenant, U. S. Navy on Divergence of Gradient Wind.

VII. SOME DYNAMIC ASPECTS OF THE TROUGH AND LOW

As was pointed out earlier, during the first and latter stages of the existence of this upper level low, the closed vortex was confined to the levels above at least 15000 feet. Only for one period of twelve hours on 20 October 1949 did a closed contour of this system appear at the 850 millibar level.

1. Friction.

Hsieh suggests the importance of frictional effects in the so-called "free atmosphere", in the building down of the rotational motion of the vortex in the cold column, by the vertical transport of momentum by eddy stresses. Hsieh uses the vorticity equation for this purpose. The increased speeds observed at higher levels coupled with the general descending motions and the conservation of momentum will cause, to some extent, the system to build to lower levels. The descending motions are approximately at the rate of one (1) kilometer per day at the 500 millibar level, and would require about four (4) or five (5) days to build down to the surface. The "cut-off" occurred at the 500 millibar level on 17 October 1949 and appeared at the surface on 20 October 1949, a period of five (5) days.

2. Vorticity.

The strength of the vortex is considered proportional to the number of closed contours surrounding the low. The number of closed contours is observed to increase as the low moves to the south and decreases as the low moves to the north. The vorticity change is then positive for the former, and negative for the latter, in qualitative agreement with the vorticity equation.

VIII. CONCLUSIONS

It must be remembered that any conclusions arrived at in this investigation are for the one upper level vortex only. It remains for further investigation to establish what properties are necessary for prognostigating the occurrence or non-occurrence of an upper level vortex of this type.

1. Trough.

Necessary of course is the development of the rather large amplitude cold trough penetrating far into the belt of the westerlies. The large amplitude being necessary to get the cold air sufficiently far south to provide a marked temperature contrast with the surroundings. The temperature distribution then assures that the trough intensifies with altitude, masking for the most part, the lower level development.

2. Residual cold dome.

The transition from a trough to a vortex requires some method for warming in the northern section of the trough. The advection of warm air appears to combine with descending motions in forming the cold core cut-off.

3. Secondary cold high.

The occurrence of a secondary cold high such as originated over the Territory of Alaska, and moved across the northern section of the trough, aids in increasing the pressure north of the low. The increasing pressure, probably resulting from upper level convergence, together with little or no change in the vortex center, causes the number of closed contours around the low to increase.

4. Vortex

The variations in height of the pressure surfaces at the center of the vortex are slight, and probably due primarily to diurnal changes. The tendency center associated with the low at 500 millibars, appears to follow the contours quite closely at that level. This is significant and should be investigated further, since prognostication of such vorticies is very important in the forecasting of upper level winds for flight operations.

The formation of a direct circulation cell to the north of the trough, as advanced by Hsieh, is not confirmed by this investigation. Instead it appears that advection of warm air and descending motions accomplish the cut-off of cold air and the vortex "cut-off". The increase of pressure, due to convergence aloft, provides the pressure gradient necessary to produce an easterly flow, and complete the closed vortex in the trough.

No attempt has been made to forecast the time of "cut-off" but to merely explain the processes which caused the phenomenon in this particular system. The 500 millibar level was utilized in this investigation; however, while unlikely, it is possible that other levels might show different results. It is interesting to note that the "cut-off" occurred at the 500 millibar level within twelve (12) hours after the 700-500 millibar thickness at station #879, reached its lowest numerical value.

For long range forecasting it would be essential to also forecast the time of occurrence of a cold trough. This is evidently related to the subject of intermittent outbreaks of cold air. A complete theory for this phenomenon is not known and is suggested for further investigation.

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